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20th International Conference on Composite Materials

19-24 JULY 2015 - COPENHAGEN • DENMARK

Multifunctional Skin Material for Morphing Leading Edge Applications

Markus Kintscher, Hans Peter Monner, Srinivas Vasista, Anton Rudenko

AFOSR Workshop on "Active Composites for Morphing Structures"

21. July 2015

Copenhagen, Denmark

DLR

Overview

- Motivation & Challenges for morphing leading edge
    - Laminarity
    - Large scale morphing
    - 3D morphing
    - „The real world“
- Aproaches for kinematics and compliant mechanisms
    - Kinematics design
    - Flexural joints
    - Compliant mechanisms design
- Approaches for skin design
    - GFRP 3D
    - GFRP-EPDM
    - GFRP with integrated layers
    - Polyurethan with foam

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Motivation & Challenges for morphing leading edge

Laminarity

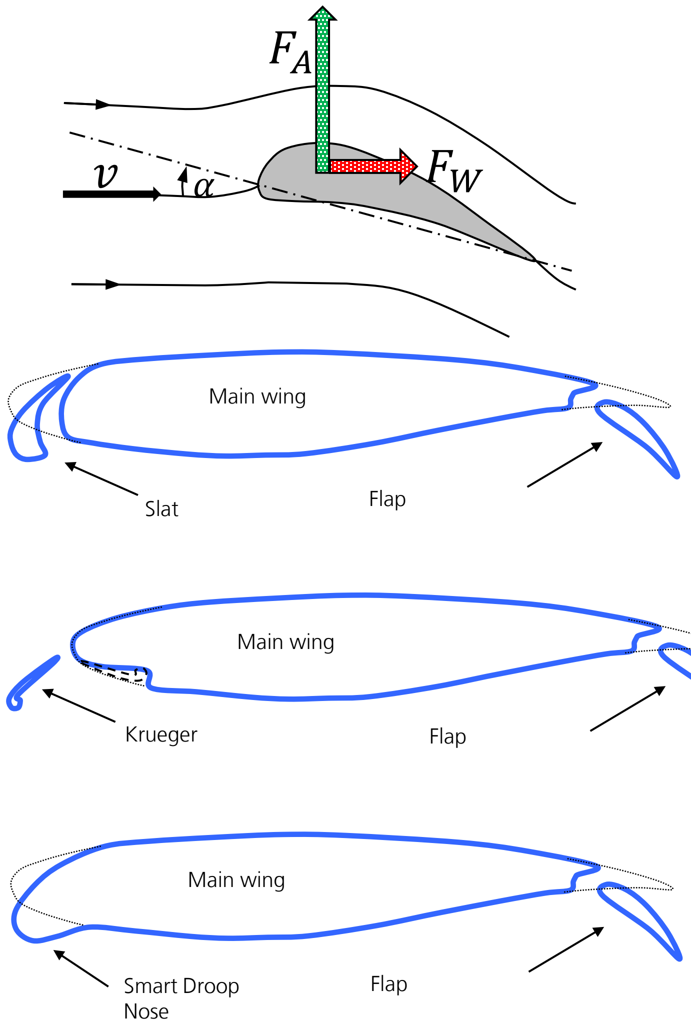
- High-Lift devices on leading and trailing edge for lift generation at low speed (take-off & landing)

- Common high-lift devices (Slat, Krueger) are highly effective ($c_{a,max}$) but exhibit slots, gaps and steps

→ Transition to turbulent flow on main wing due to steps and gaps

→ Drag due to steps and gaps

→ Primary source of airframe noise in approach/landing



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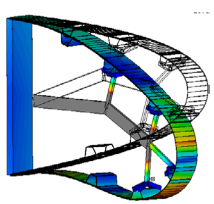
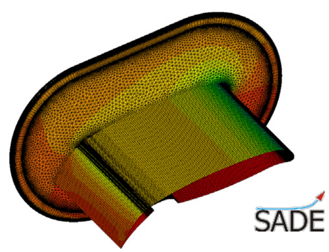
Motivation & Challenges for morphing leading edge

History of Smart Droop Nose Development at the DLR



SmartLED
2007-2010

Ground Demonstrator, 3D, Feasibility



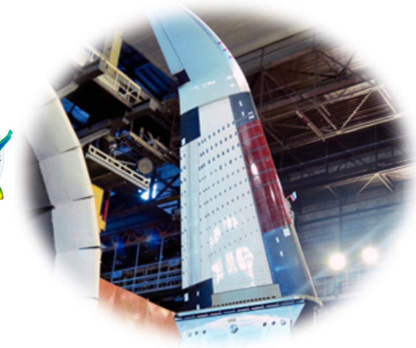
SADE
2008-2012

Wind Tunnel Model, 2D, Shape Control

JTI-SFWA
2009-2013

Hochauftrieb künftiger Verkehrsflugzeuge

Ground Demonstrator, 2D, Kinematics, Fatigue



SARISTU
2011-2015

Wind Tunnel Model, 3D, Integration of Functionalities & Shape Control & Kinematics

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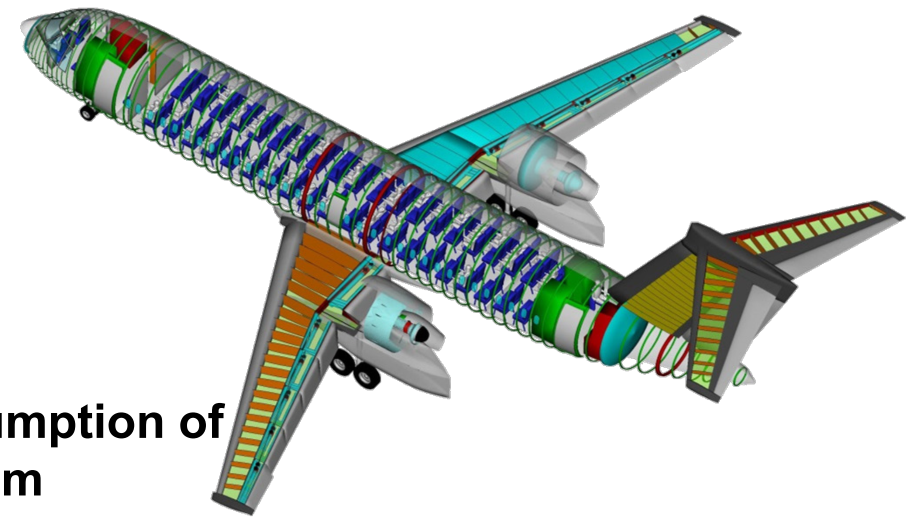
Motivation & Challenges for morphing leading edge
Large Scale Morphing

SFB 880 Hochauftrieb künftiger Verkehrsflugzeuge

Technische Universität Braunschweig

IFL

- SFB880: national special research program for the development of upstream High Lift technologies
  - Range: 2000km
  - Capacity: 100 Pax
  - STOL capability (800m)
  - Reduced level of the ground noise



→Part A: Aero-acoustics

→Part B: **Efficient High-Lift**

→Reduction of power consumption of Coanda-flap high-lift system

→Part C: Flightdynamics

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Motivation & Challenges for morphing leading edge

Large scale morphing

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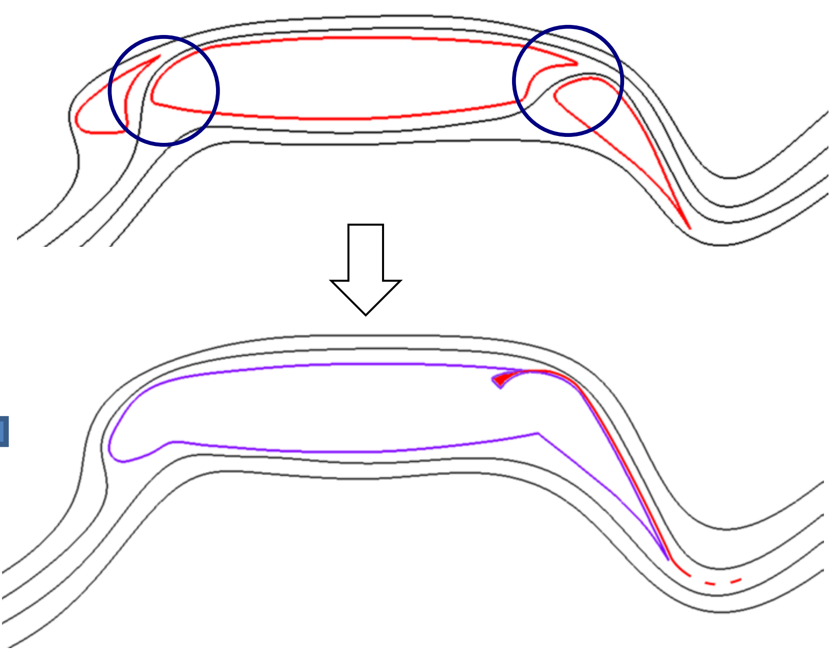
Technische Universität Braunschweig

IFL

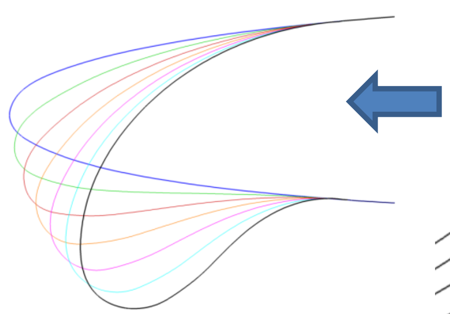
- Morphing leading edge for an active blown High-Lift system of a regional airliner
  - Gaps: noise and drag → Gapless active high lift system
  - Coanda effect is used for significantly increasing lift generation

noise sources



Cruise position

High-Lift position



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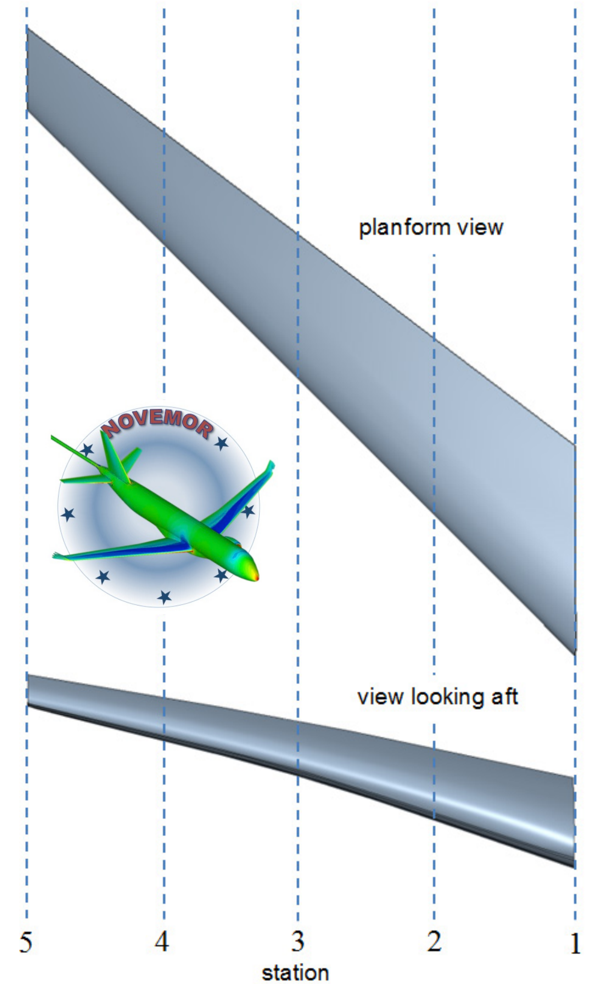
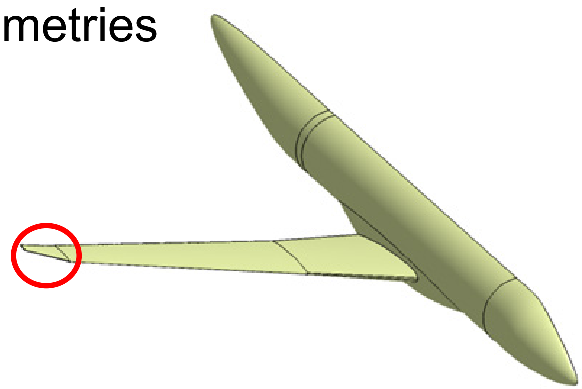
Motivation & Challenges for morphing leading edge
3D morphing

- Droop-nose morphing of a regional jet-liner wing-tip
  - Highly 3D
    - 35° sweep
    - Taper: chord and thickness
    - Dihedral
    - Double curvature
    - Streamwise morphing target shapes
  - Developing optimization tools to account for these geometries





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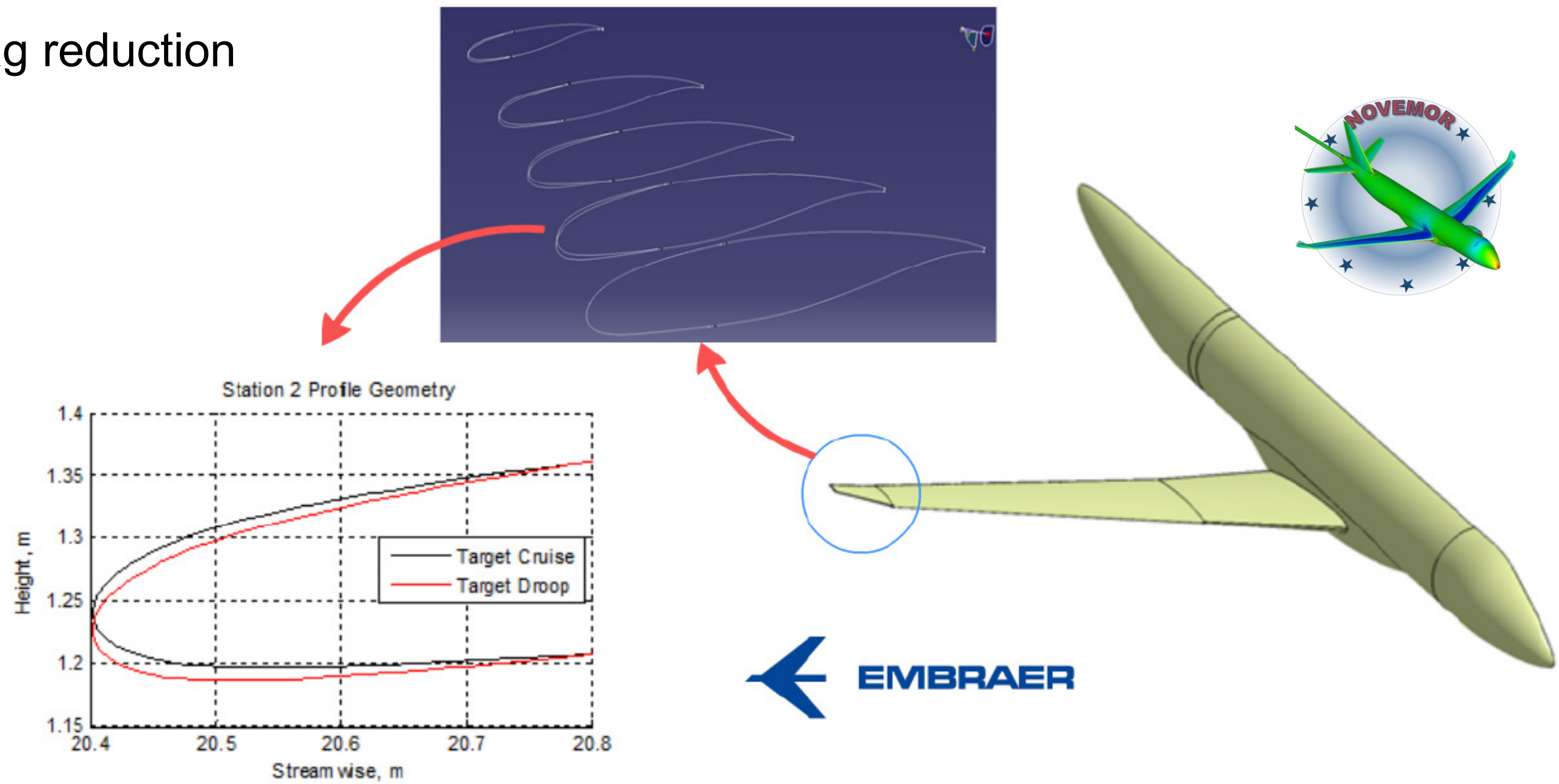
Motivation & Challenges for morphing leading edge
3D morphing

- Small morphing deflection: 2°
  - Aeroelastic benefits, e.g. prevention of aileron efficiency loss with increasing dynamic pressure
  - Drag reduction



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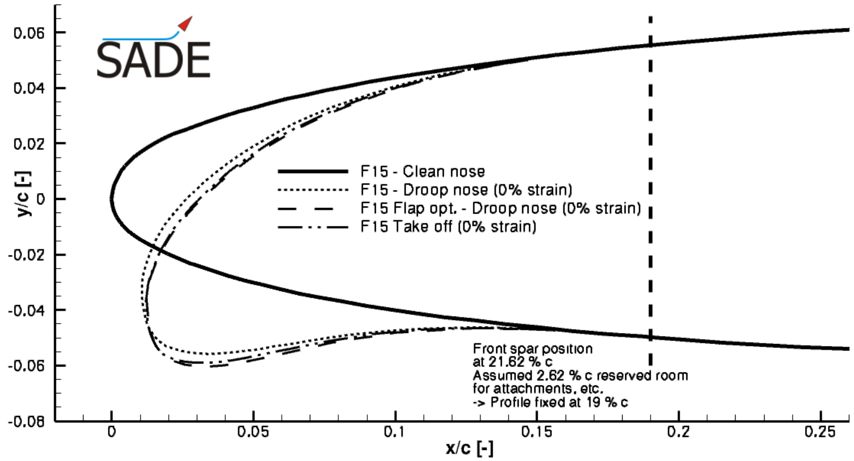
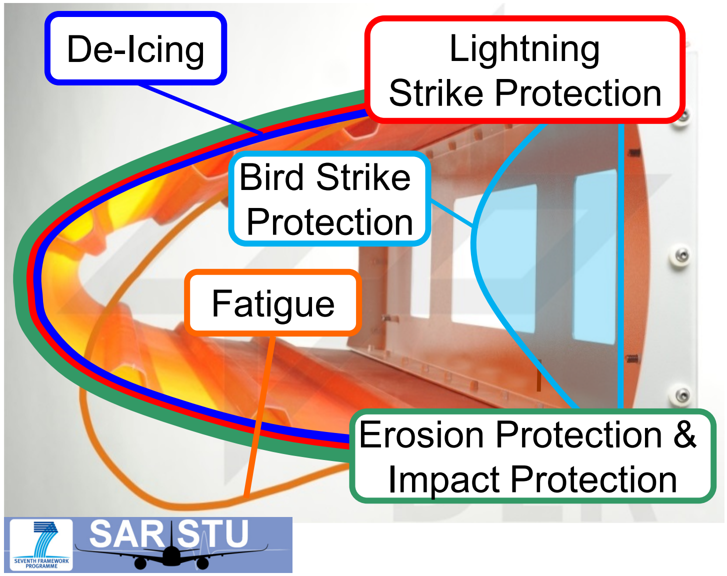
Motivation & Challenges for morphing leading edge

„The real world“



- Challenges for morphing devices
  - Large scale deformation
  - Integration of additional required functionalities
  - Concepts for integration and repair/maintenance

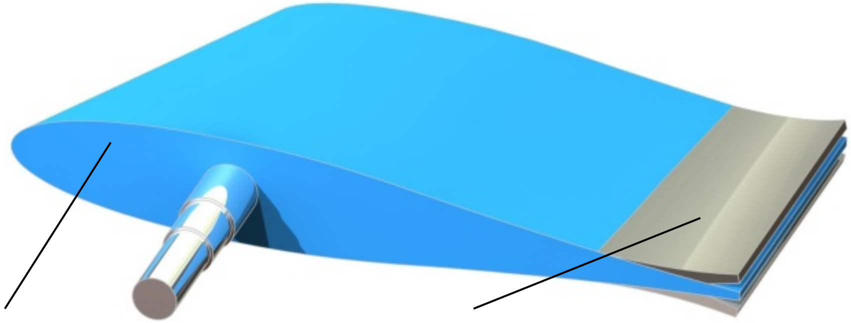


- Large Scale
  - Aeodynamic optimization of leading edge profile with max curvature difference ±20m^{-1}

Motivation & Challenges for morphing leading edge

„The real world“

- Challenges for morphing devices
  - Robustness at large scale deformation in combination with environmental conditions in operation:
  - Temperature (-50°C – +90°C)
  - Sand/Rain Erosion
  - Corrosion (skydrol, marine water, …)
- Example: Development of a morphing fin trailing edge with SKF, Blohm + Voss and partners for real life operational conditions



→SOURCE: Kintscher, M., Geier, S., Heinze, C., Pohl, M., Kamp van de, B.: Entwicklung einer flexiblen Hinterkante einer Stabilisatorflosse. DLR-Interner Bericht. DLR-IB 131-2014/22

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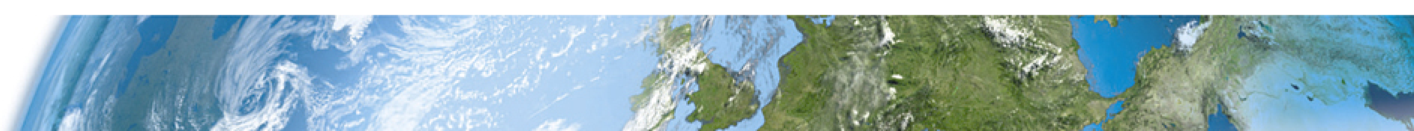
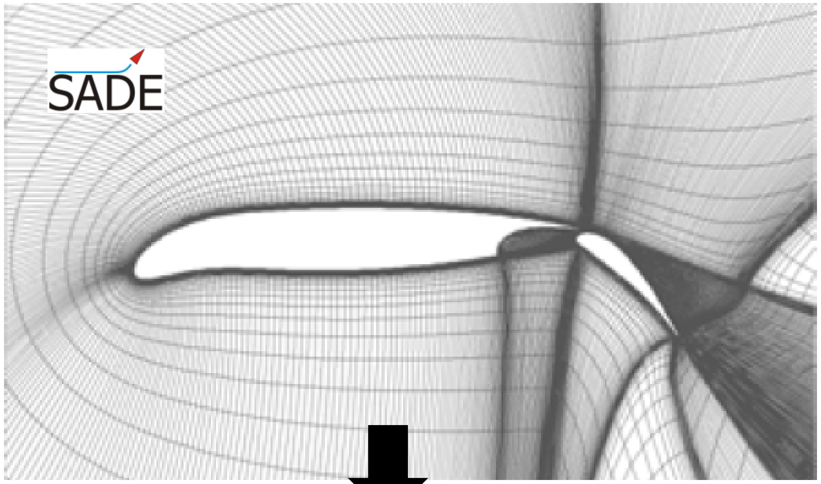
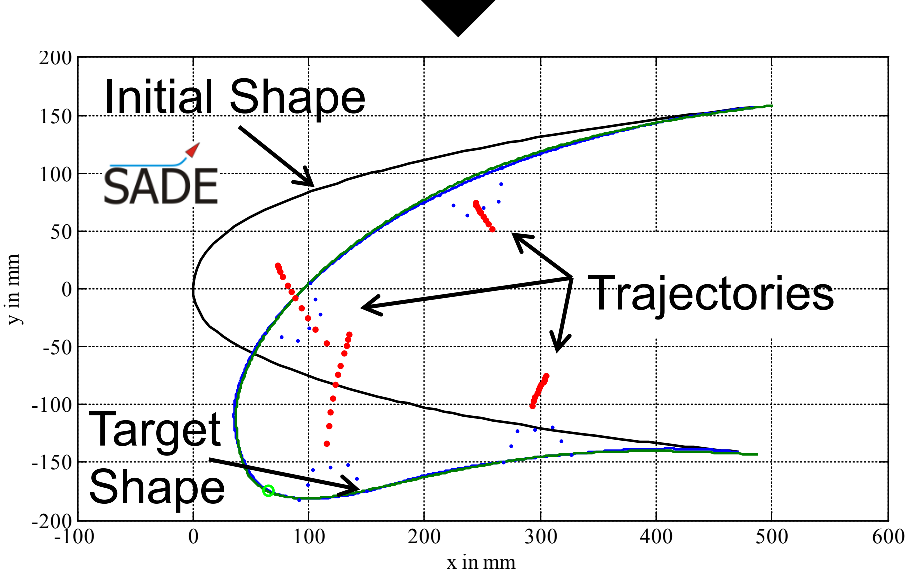


Aproaches for kinematics and compliant mechanisms

Kinematics design

- Given **Target Shape**
  - Aerodynamic or Hydrodynamic optimization
- Structural Design
  - **Interface Points** (Structure ←→ Mechanism)
- Design of Kinematics with **Trajectories**
  - Guidance Mechanism for the morphing structure during movement
  - Load transfer of aerodynamic/hydrodynamic loads

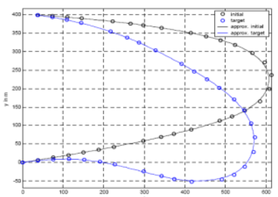




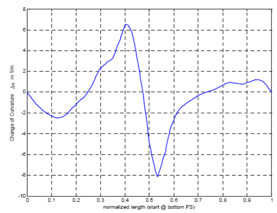
Aproaches for kinematics and compliant mechanisms

Kinematics design

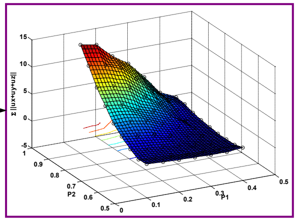
- Pre-Design of Skin and Kinematics (2D)



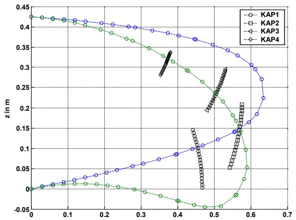
Aerod. Target Shape



Initial Skin Design



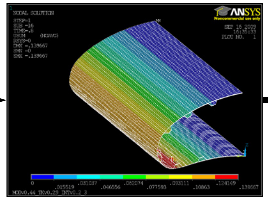
2D parametric FE,
Optimal Support Pos.



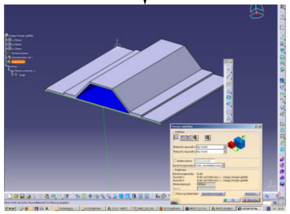
Kinematical Path, Strains, Deformations, Stresses

SADE

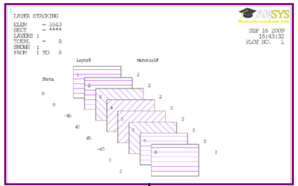
- Detailed Design (3D)



3D FE model



Optimization of the Design of Omega-Stringers wrt. stability and strength requirements



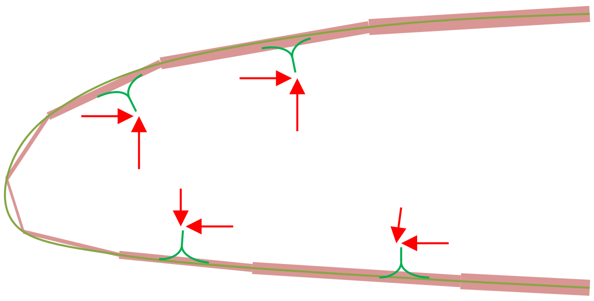
Optimization of layer stacking sequence/ laminate layup wrt. target shape, stability and strength requirements

Feedback data for other disciplines

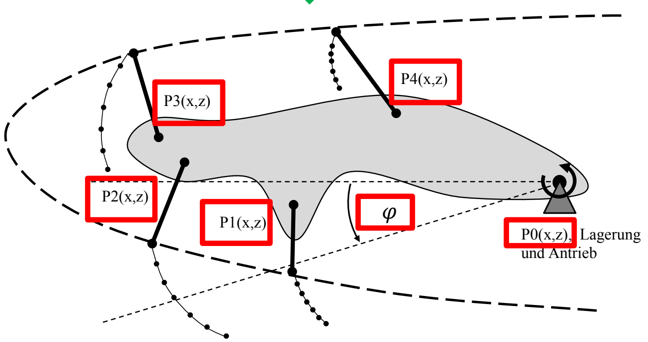
Aproaches for kinematics and compliant mechanisms

Kinematics design

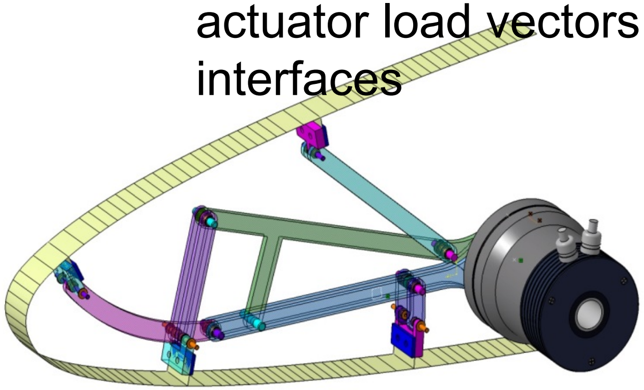
- **Design parameters** of the skin optimization:
    - Stiffness of skin segments along the skin perimeter
        - Thickness or layup variation, …
    - Positions of the interfaces to the compliant kinematic system
    - Modulus and the direction of the actuator load vectors on these interfaces



Optimization of the skin and skin-to-kinematic interfaces

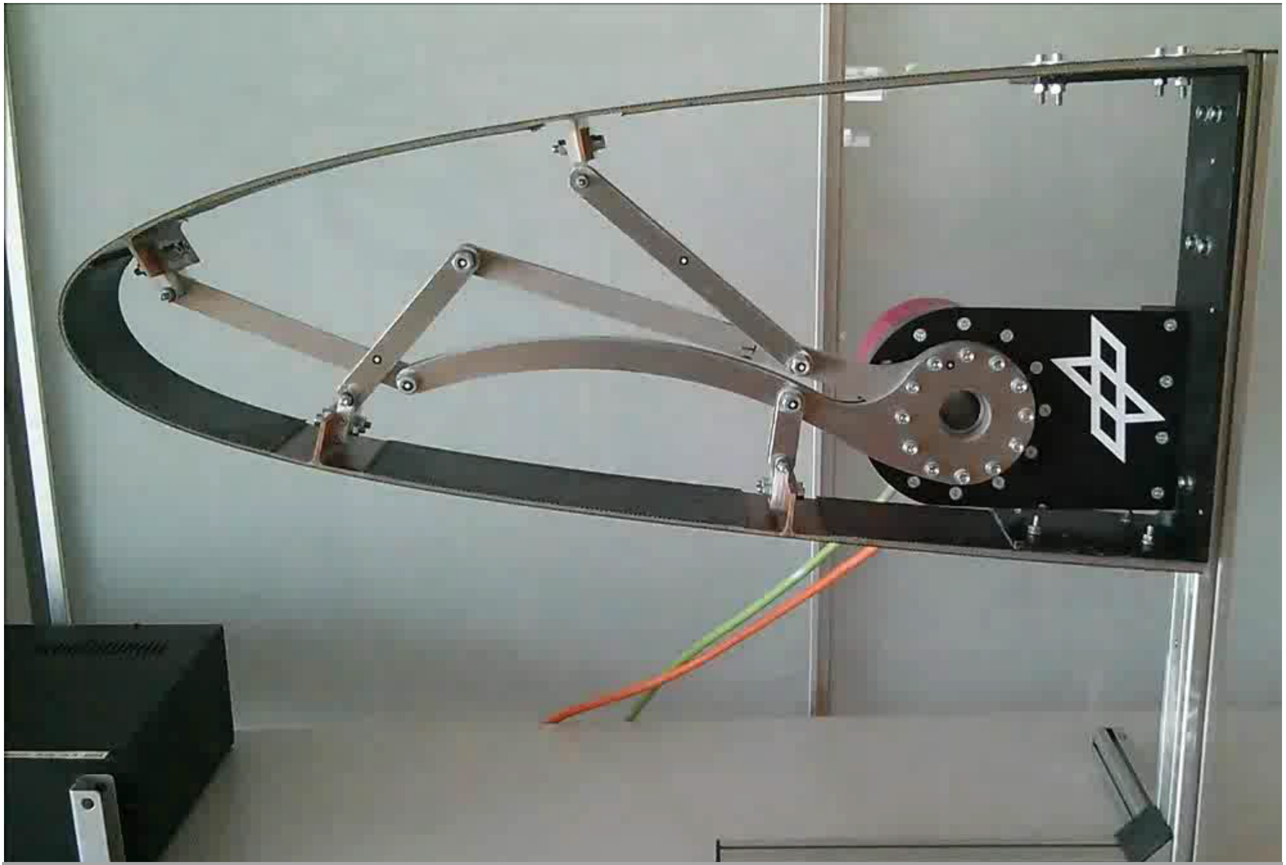


Optimization of the inward kinematic



CAD-construction of the morphing leading edge

Aproaches for kinematics and compliant mechanisms
Skin & Kinematics design (large scale morphing)



Full-Scale morphing droop nose demonstrator

Hochauftrieb künftiger Verkehrsflugzeuge SFB 880

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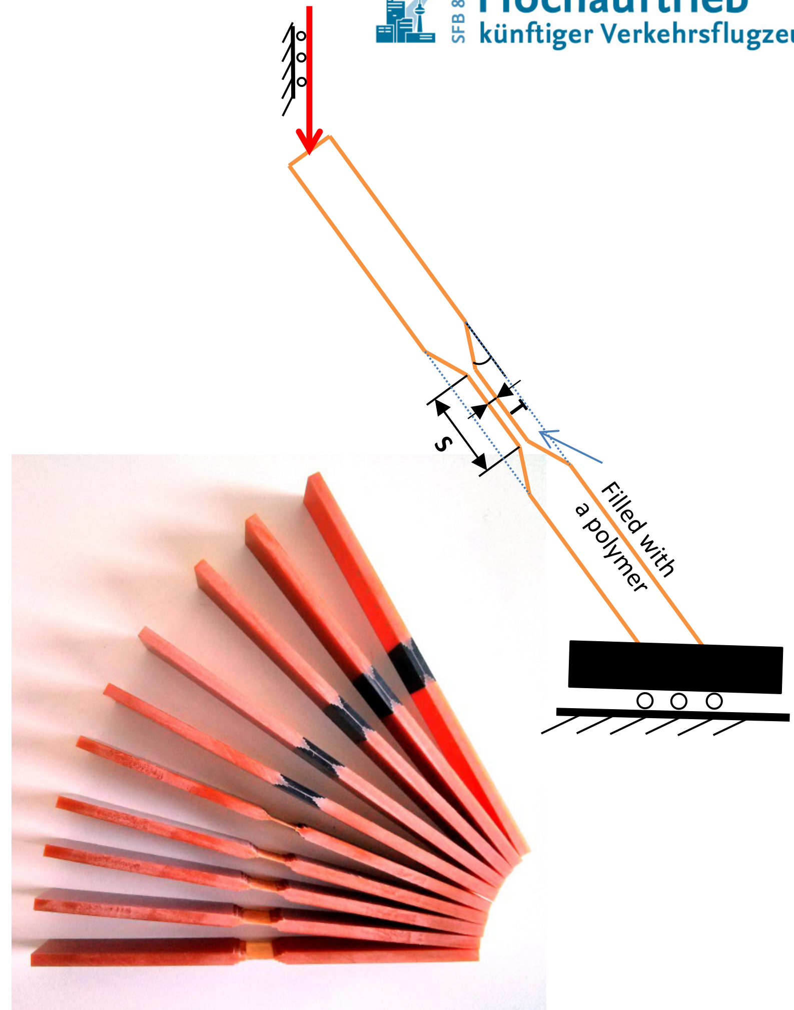
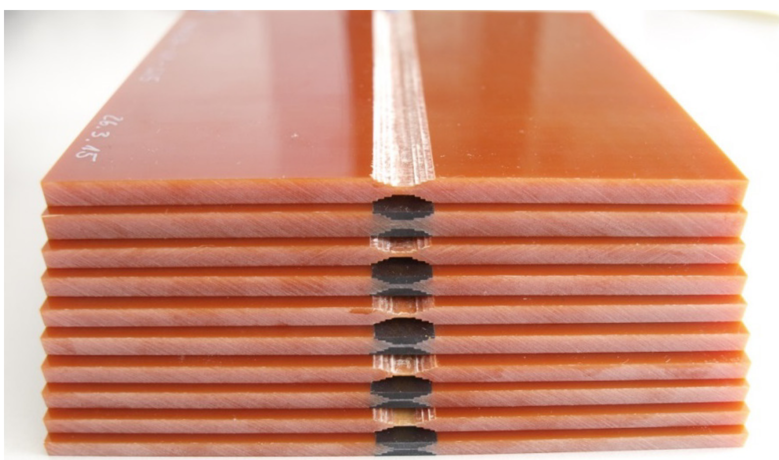
Aproaches for kinematics and compliant mechanisms

Flexural Joints for Compliant Mechanisms

- Substitution of the state of the art kinematics by flexural joints and compliant mechanisms

- Numeric and experimental parametric studies on GFRP-Polymer joints under multiaxial loading





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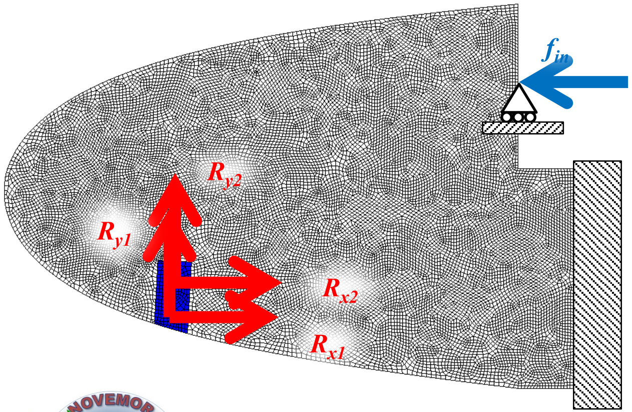
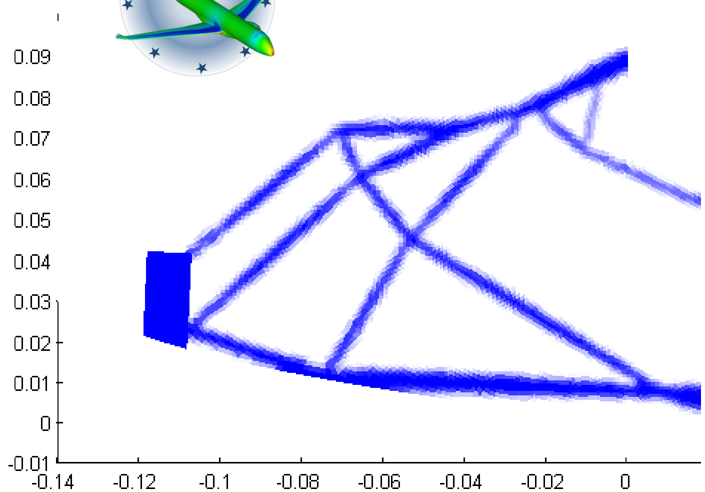
Aproaches for kinematics and compliant mechanisms
Compliant mechanisms design

Advantages of Compliant Mechanisms
- lightweight structures
- reduced assembly complexity
- no backlash

Topology Optimization
- find best structural layout starting from a "blank canvas"
- continuum gradient based via SIMP, sensitivity analysis and MMA
- 2D plane stress
- linear FEA routine (small target deflections)
- Shape control formulation: precision displacement
- Stiffness functions: load capability





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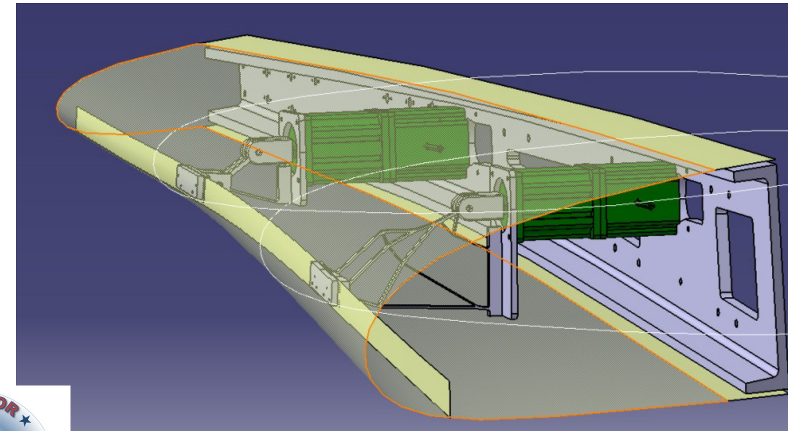
Aproaches for kinematics and compliant mechanisms

Compliant mechanisms design

- Topology post-processed
- Superelastic nickel titanium (>2% strain)
- Manufactured by wire electrical discharge machining (EDM, 5 mm plate form)



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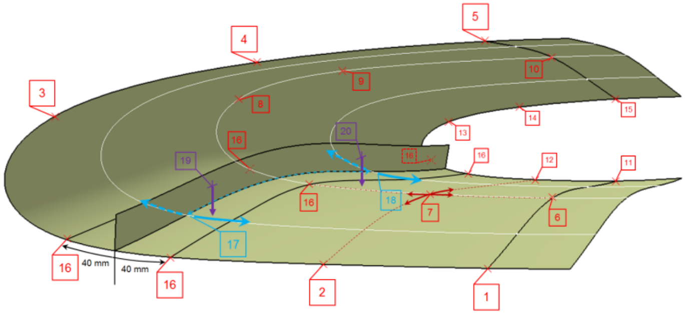
Approaches for skin design
GFRP 3D



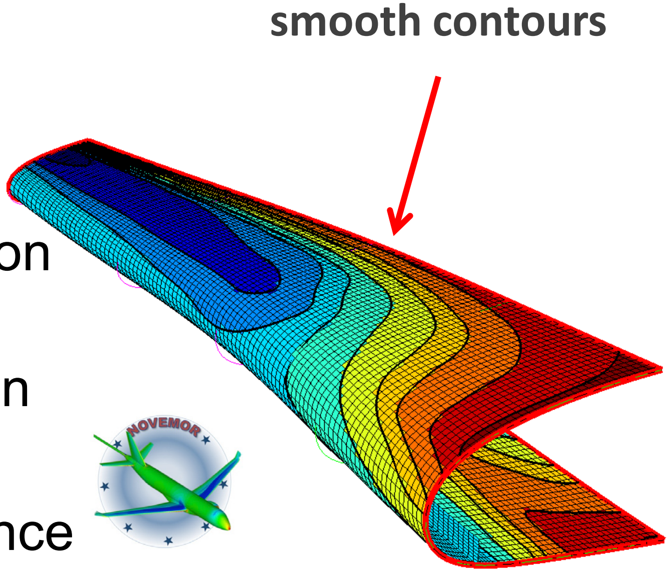
- tailored stiffness:
  - optimized skin thickness distribution
- thickness achieved via appropriate ply stacking
- GFRP Hexcel HexPly® 913 prepreg plies
- skin – compliant substructure interface: stringer
  - i.e. load introduction point
- 2D concept of SADE program →
  - Re-developed in a 3D environment in NOVEMOR
- Simplex algorithm
- automated and iterative
- objective function: LSE clean and droop configurations
  - multiple FEA solutions via Ansys:
    - combined shape change and stiffness functionality

DVs 1 – 16:
- skin thickness at 21 points
- [1 – 4] mm
- bilinear interpolation

DVs 17 – 18:
- stringer position at stations 2 and 4
- [35 – 55] % station perimeter length
- spline interp. and extrap.

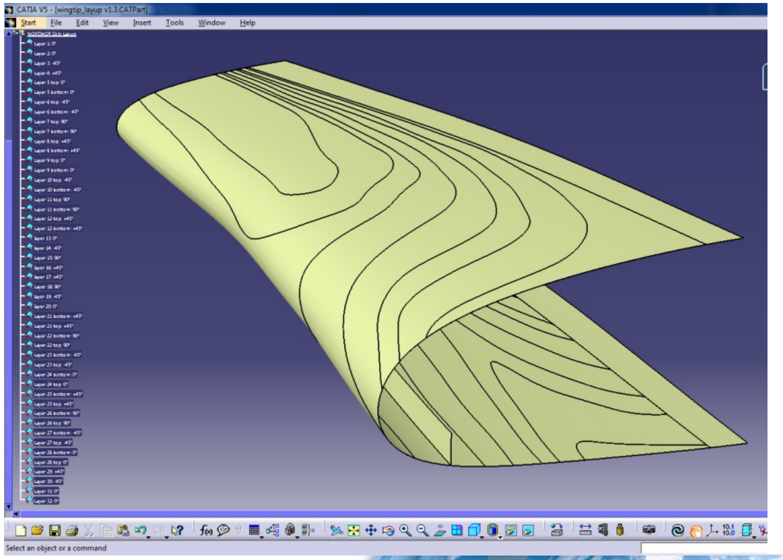
DVs 19 – 20:
- force magnitude at CM stations
- [50 - 650] N

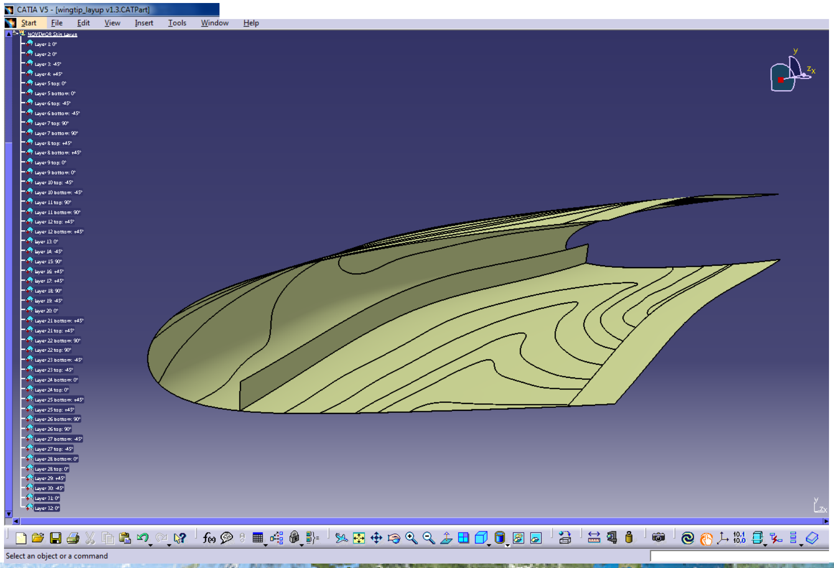
Approaches for skin design
GFRP 3D



3DSkinOpt post-processing

- algorithm established for ordered edge detection
- LSE 3D spline-fit based on coordinate parameterization for smooth contour generation
- export files to CAD
- 32 plies (HexPly® 913) as per stacking sequence





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Approaches for skin design
GFRP 3D

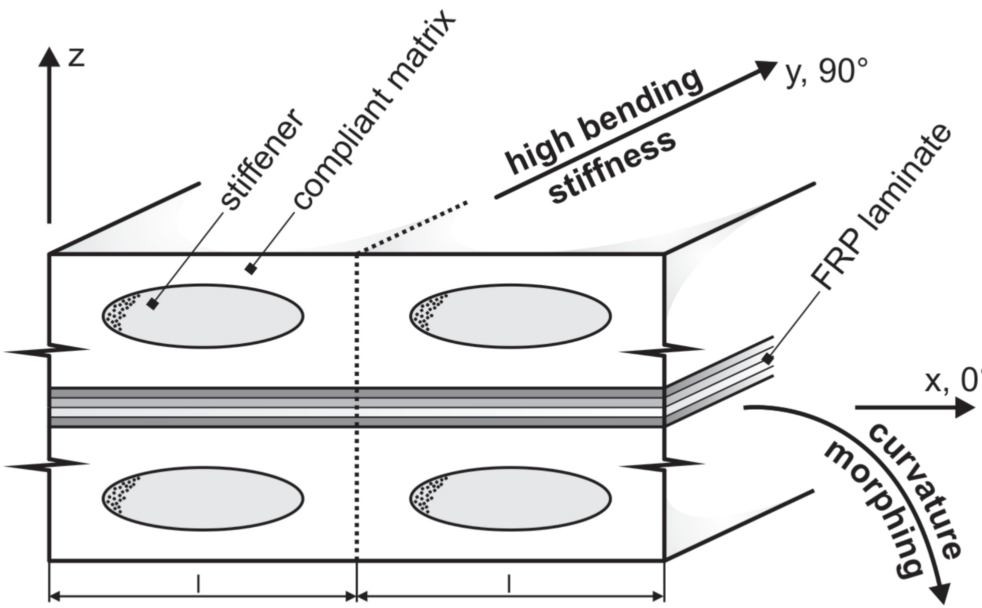


Wind tunnel tests, Feb. 2015

- Univ. of Bristol, 7' x 5' Low speed
- Assessment of structure (skin and compliant mechanisms) under aerodynamic loads

Approaches for skin design
GFRP-EPDM

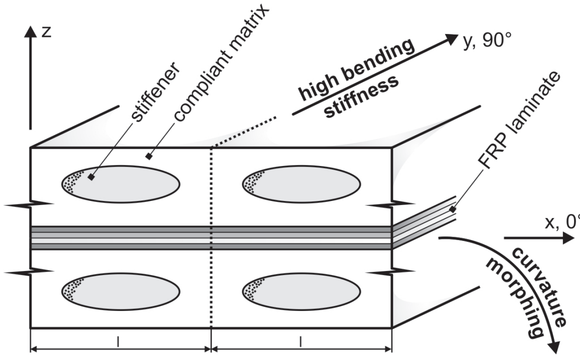
- Hybrid skin design for high anisotropic skins
- High-Strain capability through combination of GFRP/EPDM-rubber (synthetic rubber)
- Combination of GFRP laminate with C/GFRP stiffeners in a rubber matrix
- Flexibility in chord direction – stiffness in span direction

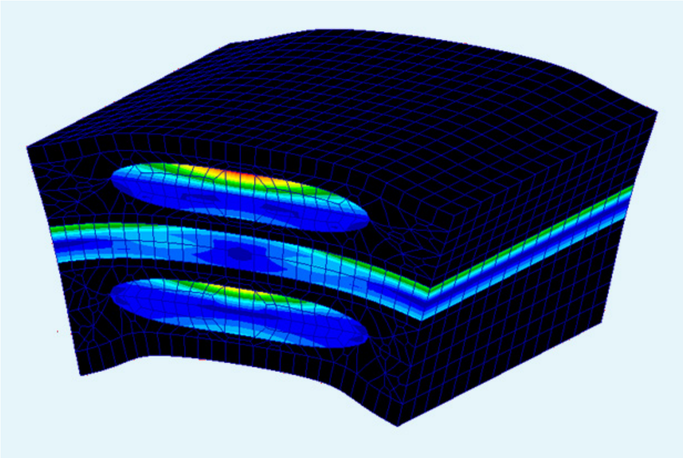


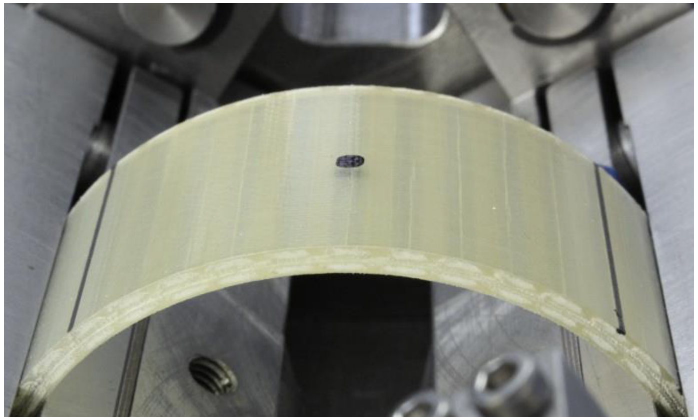
Source: Andre Schmitz, IFL, TU-Braunschweig

Approaches for skin design
GFRP-EPDM

- A representative FE-element of a hybrid skin under bending load
  - Parametric boundary conditions
  - Reduced order modeling for large scale applications
- Experimental validation of the FE models
- Strength and fatigue investigations







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Approaches for skin design
GFRP-EPDM

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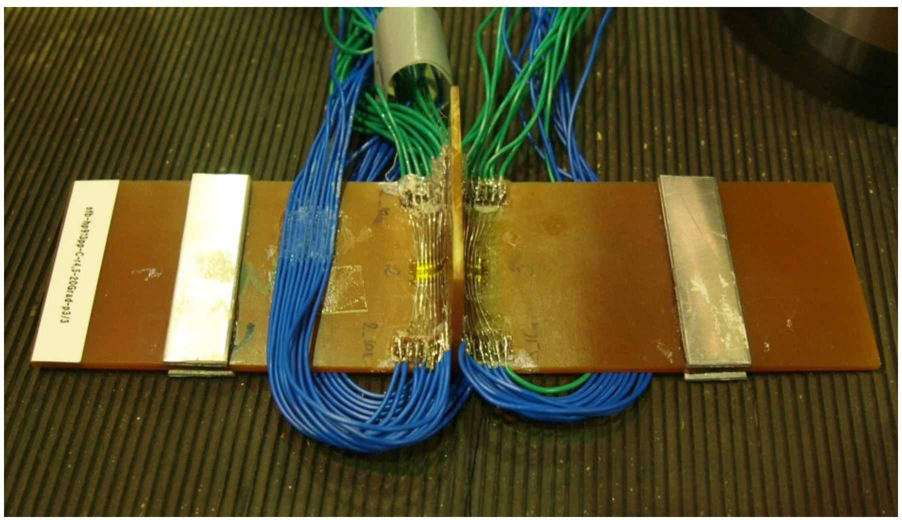
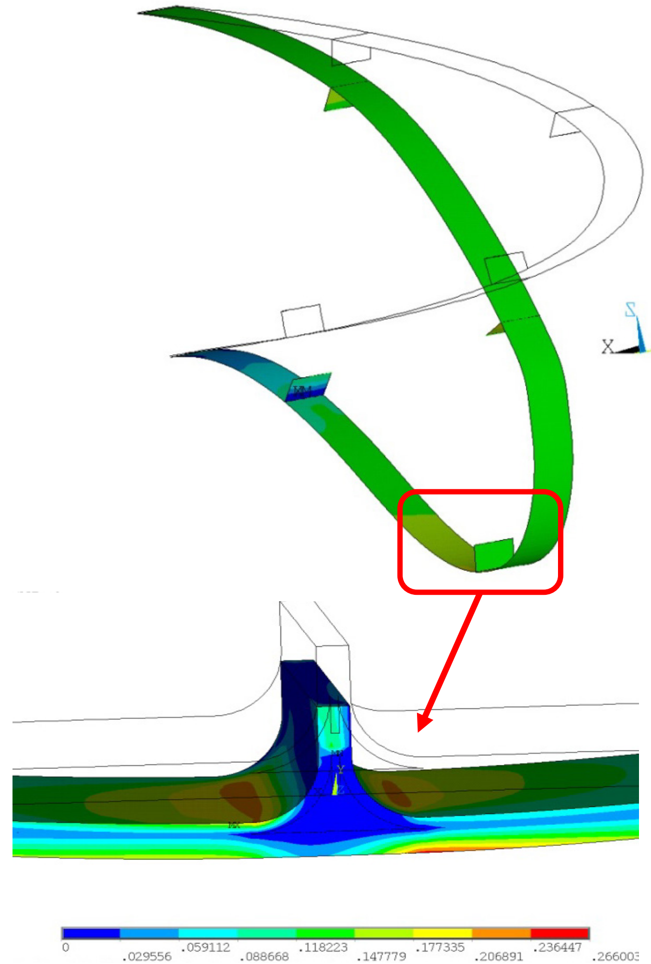
- Experimental and numerical investigations on the skin-kinematic interfaces
- Integration of dense meshed solid models in the optimization routines



A specimen with 30 micro strain gages in curved surfaces for the model validation



Investigation of strength of load application points under representative loading conditions (curved)

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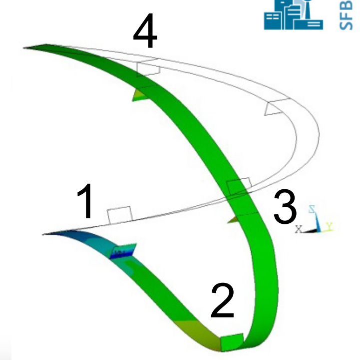
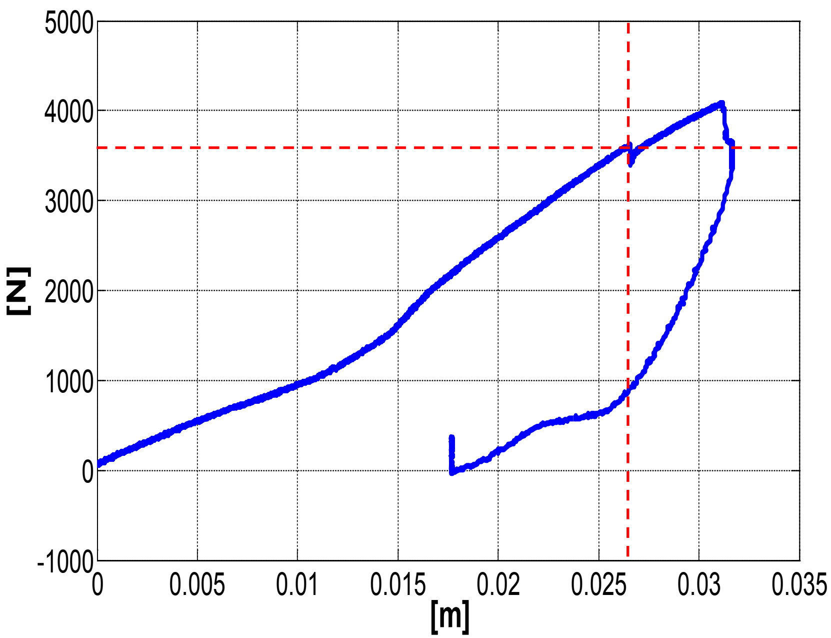
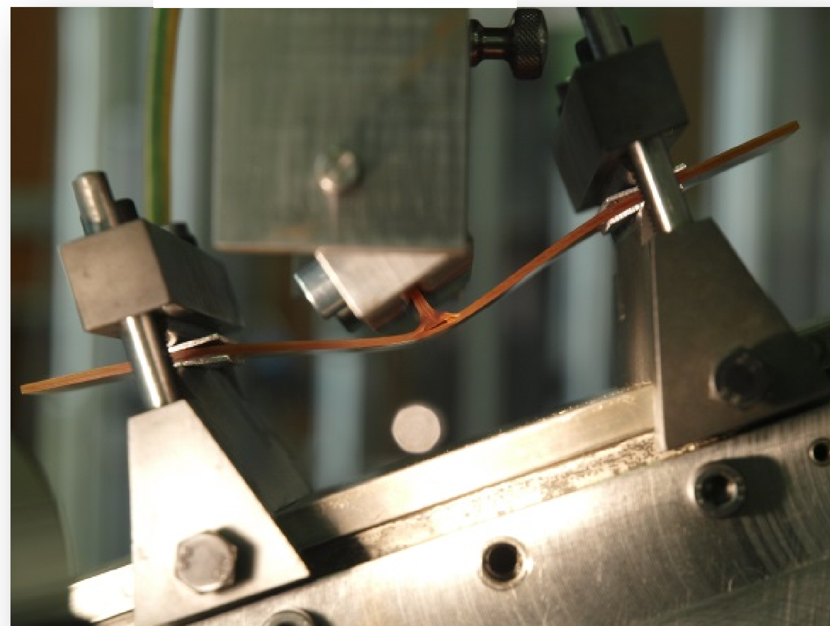
Approaches for skin design
GFRP-EPDM



- Strength of the interface under realistic loads



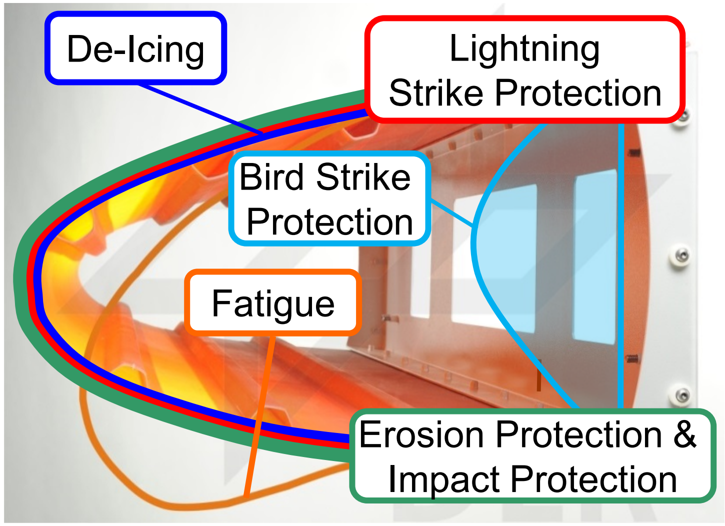
Force – Displacement Curve of loading under 20°force application



Test of a double-L interface with a force under 20° load application

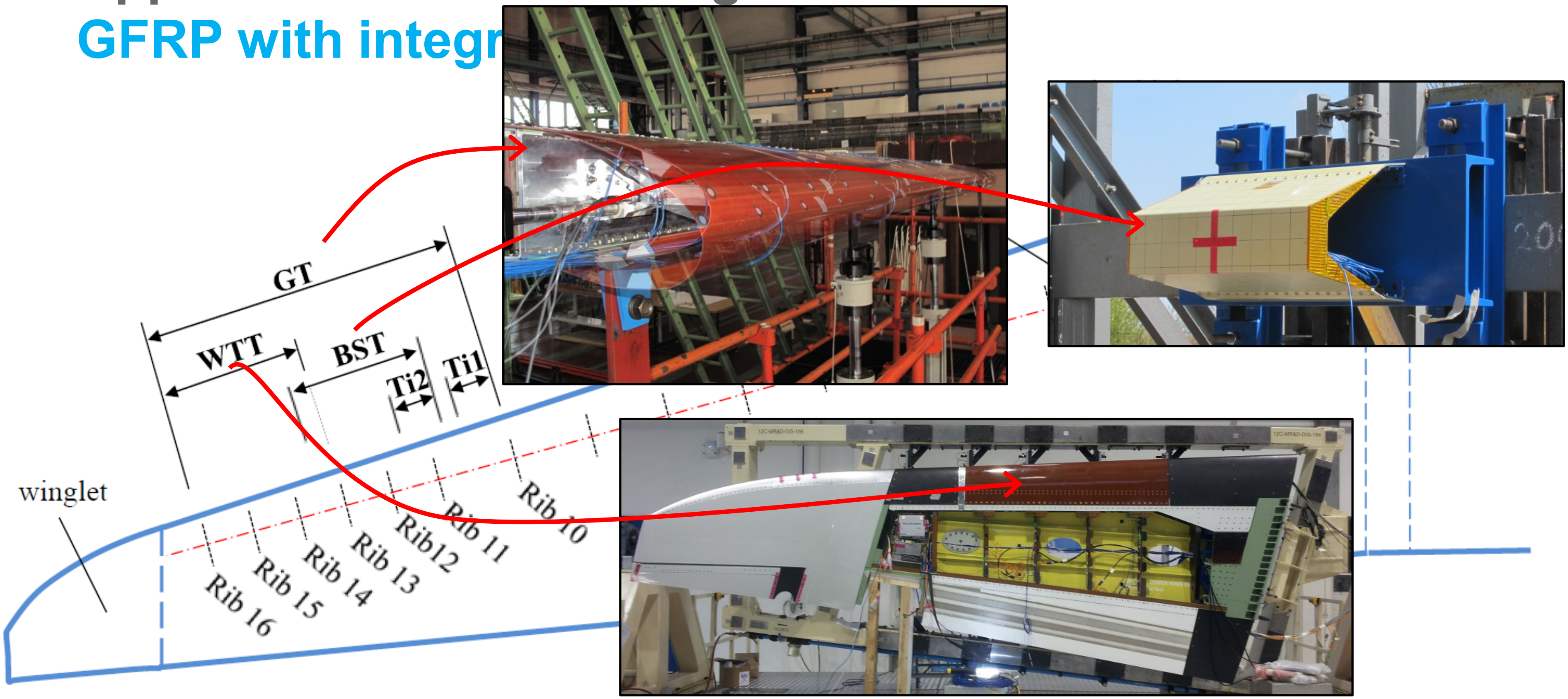
Approaches for skin design
GFRP with integrated layers

- Integration of additional functionalities into a ‚baseline' GFRP skin concept
  - Ice Protection System (IPS)
  - Lightning Strike Protection (LSP)
  - Erosion & Impact Protection
  - Bird Strike Protection
  - Improved Fatigue Behaviour



Approaches for skin design

GFRP with integr



Acr.	Rib Station	Length	Test/Demonstrator	Topic
GT	Rib 10 – Rib 16	3656mm	Large scale test: wing bending, cyclic, heater-mat	Shape, Strain, Strength
WTT	Rib 13 – Rib 16	1760mm	Test under aerodynamic loads	Shape, Strain
BST	Rib 11 – Rib 12	1600mm	Bird Strike Tests, 3 configs: 2x splitter, 1 hybrid	Bird Strike Performance
Ti1	Rib 10	300mm	Demontrator with Ti-foil (full-chord) & heater-mat	Shape
Ti2	Rib 11	300mm	Small scale test with Ti-Foil (Patch)	Shape, Strain, Strength

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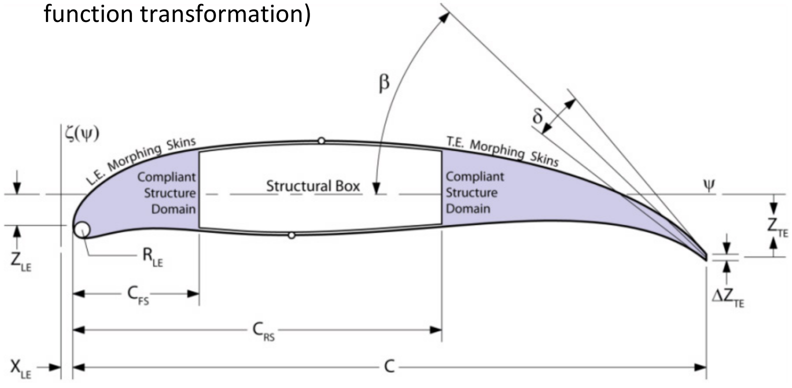
SMART INTELLIGENT AIRCRAFT STRUCTURES

Approaches for skin design
GFRP with integrated layers

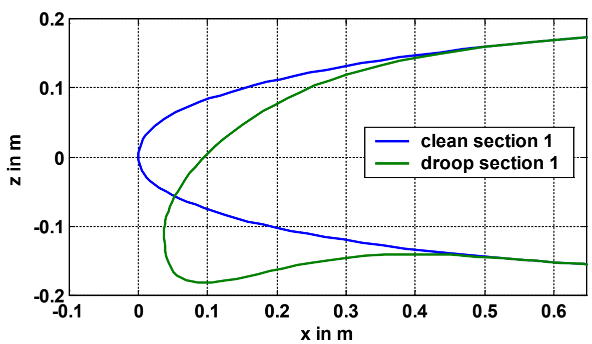
→Basic Design Specifications
→(Pre-) Design based on target shapes

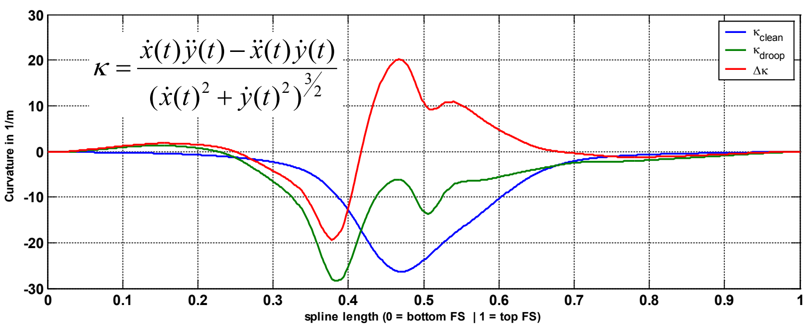
- **Parametric Description of aerodynamic profile**
- **Aerodynamic Optimization (High-Lift, Cruise(VC))**
- **Assessment of Structural (Geometric) Boundary Conditions**

Parameterization of the profile for CST method (class/shape function transformation)



Source: S. Ricci, A. Gaspari: "Combining Shape and Structural Optimization for the Design of Morphing Airfoils", 2nd International Conference on Engineering Optimization, September 6{9, 2010, Lisbon, Portugal





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Approaches for skin design
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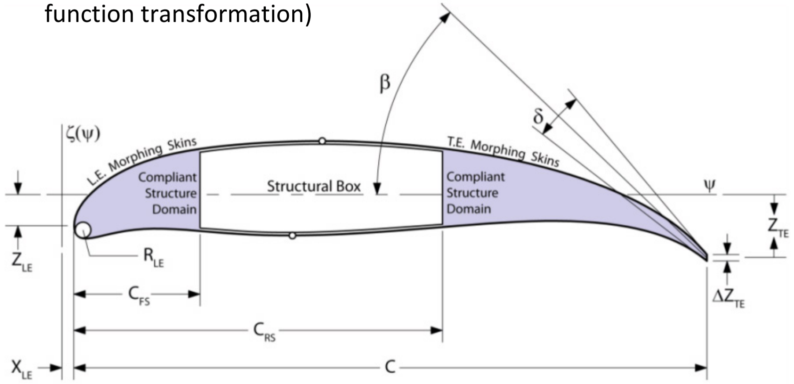

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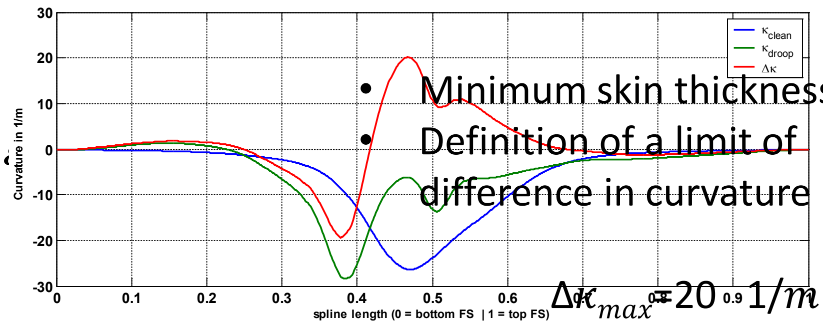

- Minimum skin thickness
- Definition of a limit of difference in curvature

$\Delta\kappa_{max} = 20\ 1/m$

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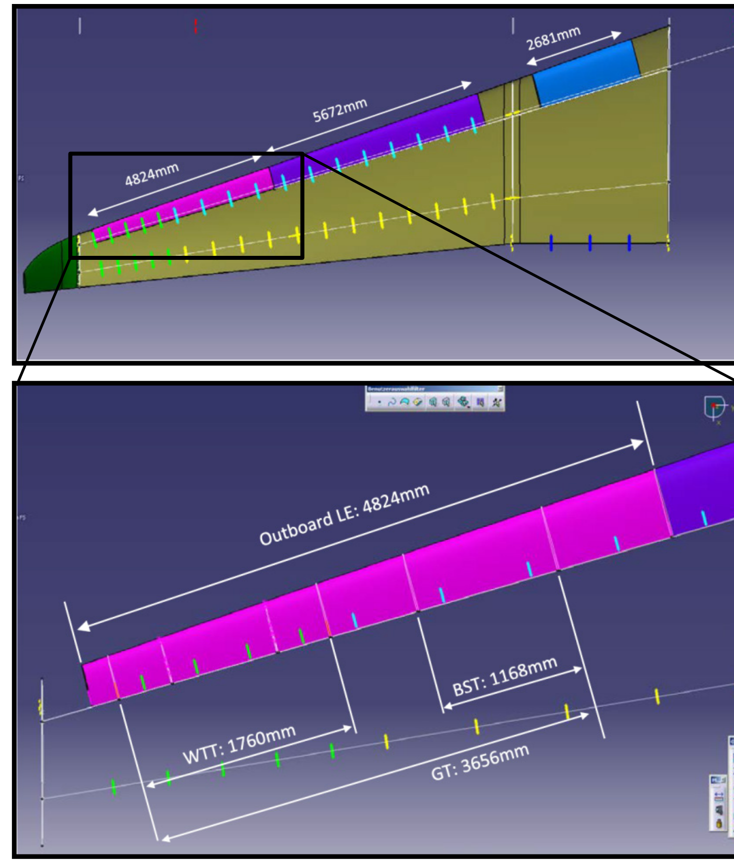
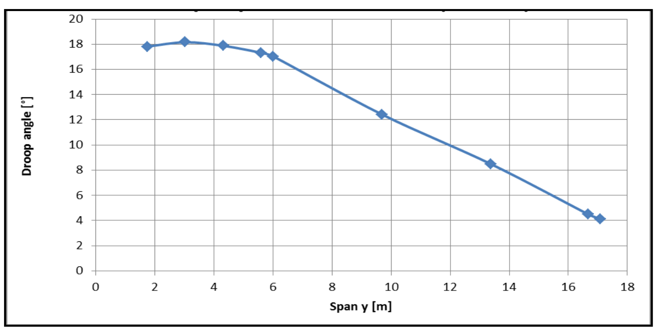
Approaches for skin design
GFRP with integrated layers

"Integrated Structure and System Concept Definition"

- **Overall wing leading edge sections**
  - Three leading edge sections
    - Two Outboard Sections
    - One Inboard Section
  - Kinematic Stations are consistent with given rib positions
- Integration of bird strike protection and kinematics
- Integration of additional functional layers





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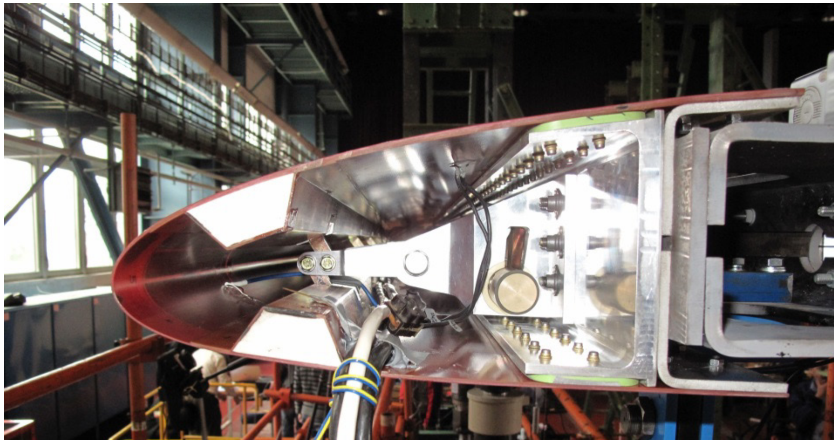
Approaches for skin design
GFRP with integrated layers

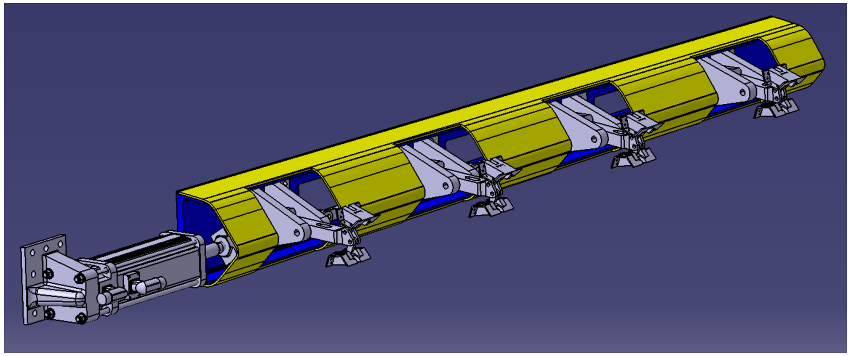
"Integrated Structure and System Concept Definition"

- Overall wing leading edge sections
    - Three leading edge sections
        - Two Outboard Sections
        - One Inboard Section
    - Kinematic Stations are consistent with given rib positions
- **Integration of bird strike protection and kinematics**

→ Design Space is limited!

- Integration concept of additional functional layers





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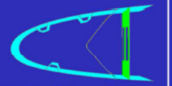
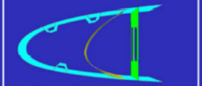
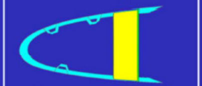
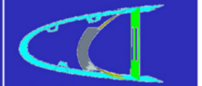
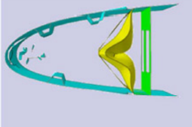
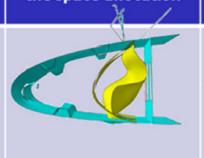
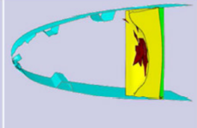
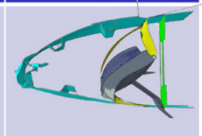
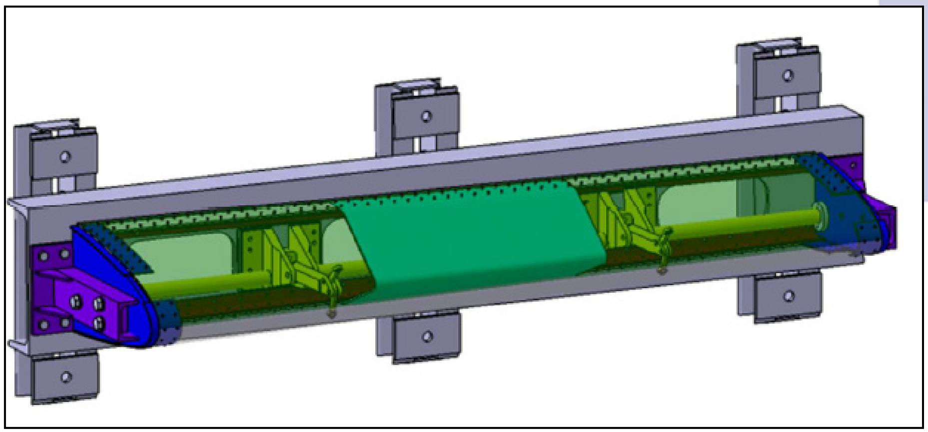
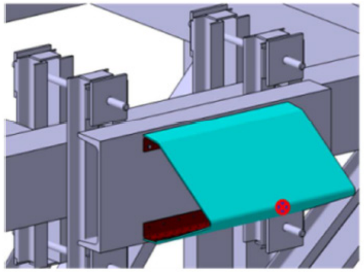
Approaches for skin design
GFRP with integrated layers

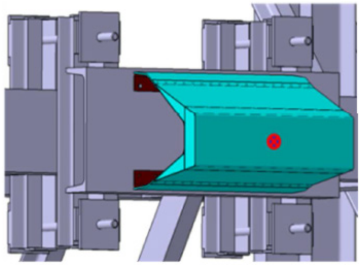
→Integration of bird strike protection and kinematics

- **Shot on morphing leading edge with integrated bird splitter and separate hybrid splitter concept**

	Concept 1	Concept 2	Concept 3	Concept 4
	 Bird Splitter with a circular edge in the nose	 Inner Dnose skin, designed to maximize the space allocation	 Honeycomb panel attached to the subspar.	 Combination of the inner Dnose and the honeycomb panel concept.
Final BSPS Damage				
BSPS masses	2.18 Kg	2.63Kg	3.19Kg	3.43 Kg
Spar protection	Not impacted	impacted	plastified	Not impacted
System Space allocation	Probably not sufficient	Better than concept 1	No space allocation	Better than concept 1
Scenario Description	• Nose skin perforated . • Acting as a bird splitter. • BSPS is higlhy deformed and locally torn. • bird is split and is flowing along the slopes of the BSPS, it leads to the bottom and top failure of the nose skin but the spar is protected.	• Nose skin perforated . • Bird is draging away the BSPS toward the subspar, the spar is finally impacted. • The BSPS is higlhy deformed and locally torn. • A part of the bird is flowing along the BSPS and perforate the nose skin.	• Bird stopped • Spar plastified	•Nose skin perforated • BSPS is higlhy deformed and plastified. • the majority of the bird kinetic energy is absorbed . •A part of the bird is flowing along the BSPS and perforate the nose skin but the spar is protected.







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Approaches for skin design
GFRP with integrated layers

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Approaches for skin design
GFRP with integrated layers





Approaches for skin design
GFRP with integrated layers

"Integration of additional functionalities"

- Overall wing leading edge sections
- Integration concept of BSPS and kinematics
- **Integration concept of additional functional layers**
  - Surface Protection
  - De-/Anti- Icing
  - Impact Resistance
  - Lightning Strike Protection

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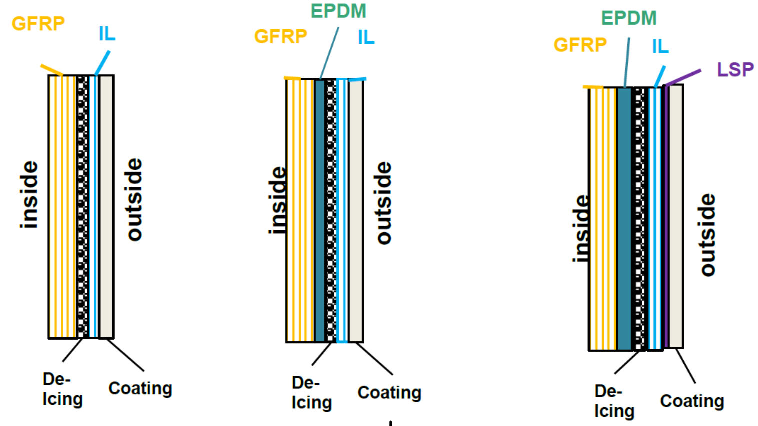
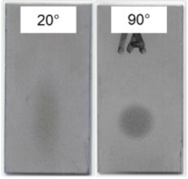
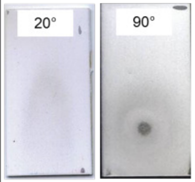
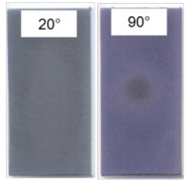
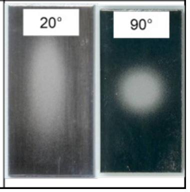


Comparison of rain and solid particle erosion durability of different materials

	Metall	Paint	Rubber	Hard coating
Rain erosion (20 – 3000 impacts, 225 m/s, 2 mm drop size)				
Solid particle erosion (5 g silica sand 220 µm, 55 m/s, 2 g/min)				

Approaches for skin design
GFRP with integrated layers

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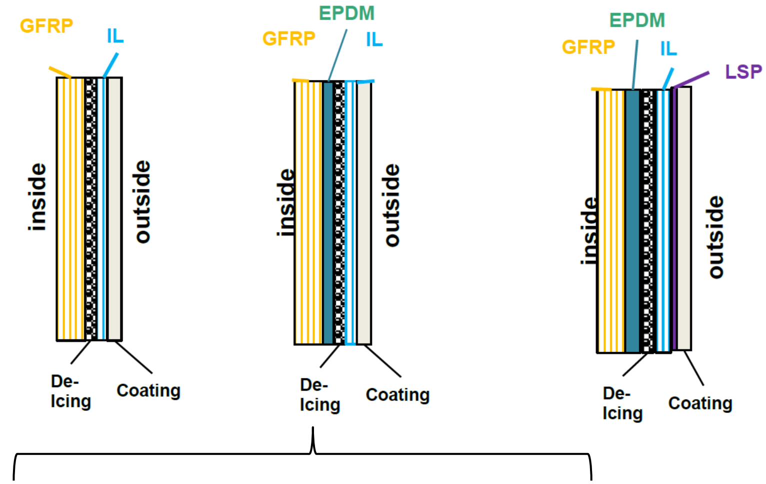

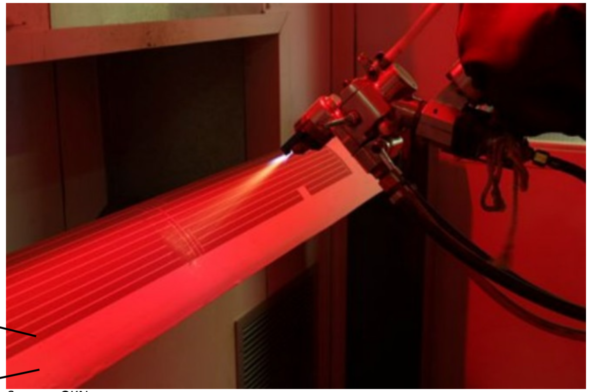

Source: GKN

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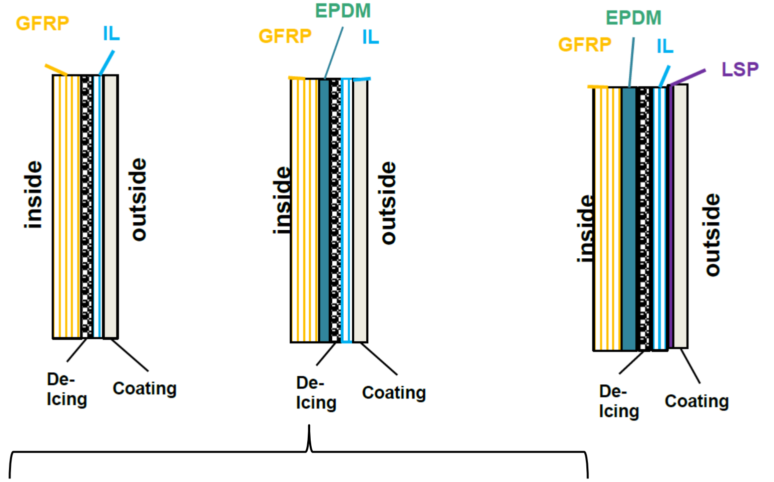

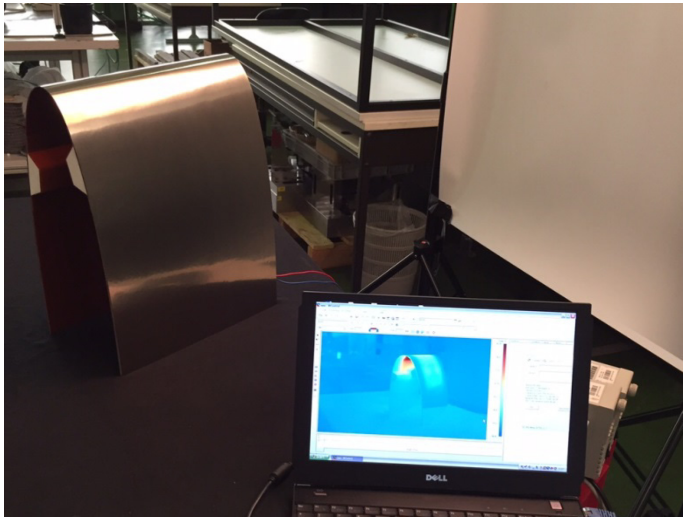

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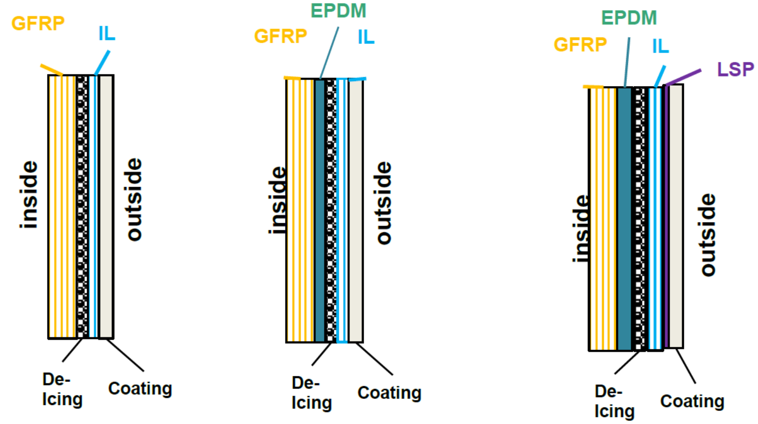

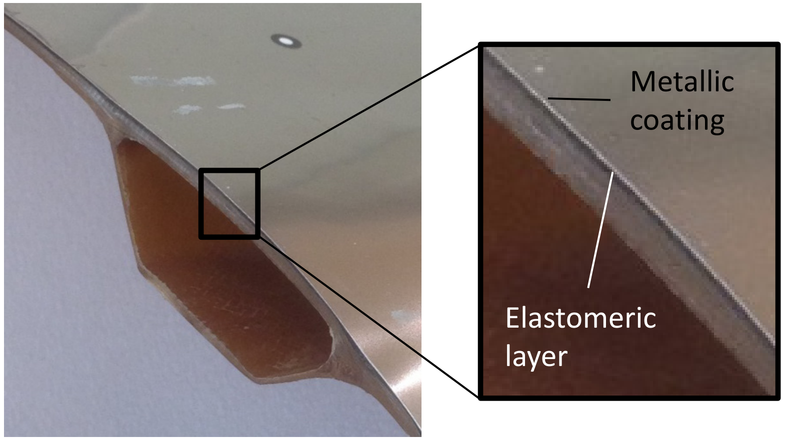

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Approaches for skin design
GFRP with integrated layers

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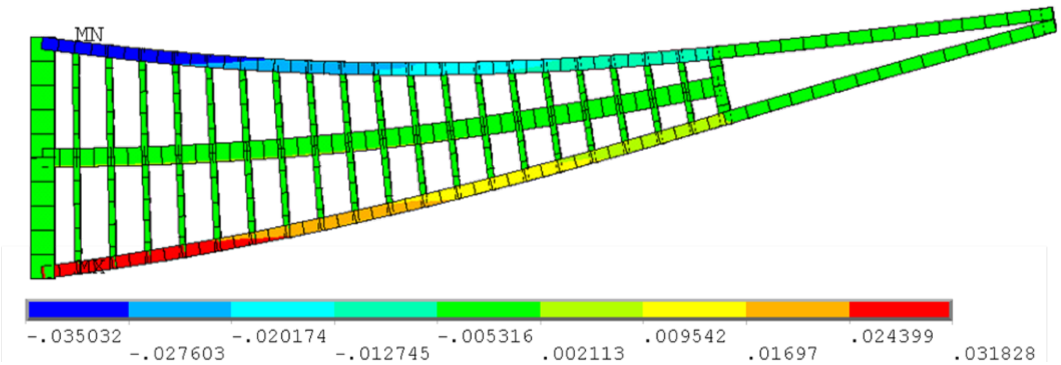
- Limited Design Space at outboard: Integration brackets can be realized but lead to strain peaks (which limit the degree of morphing) and local stiffening in chord (which increases local changes in curvature when deployed, waviness)
- Metallic erosion protection shields make the tailoring to target shapes difficult due to their high stiffness and exhibit a poor fatigue behavior
- Max. Strain: Functional Layers to be integrated must be high strain capable and must be designed as thin as possible
- IPS: The dielectric properties of the basic material must be improved. It triggers additional thickness due to electr. isolation and for their part again higher heater-mat temperatures due to thermal isolation
- Lightning strike protection without application of metallic foils needs to be investigated

Approaches for skin design
Polyurethan with foam

- Structural Concept for a Morphing (FIN) Trailing Edge



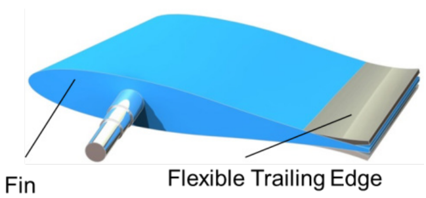


Fig.: Pre-Design Finite Element Analysis: Strain Distribution in Deployed Position

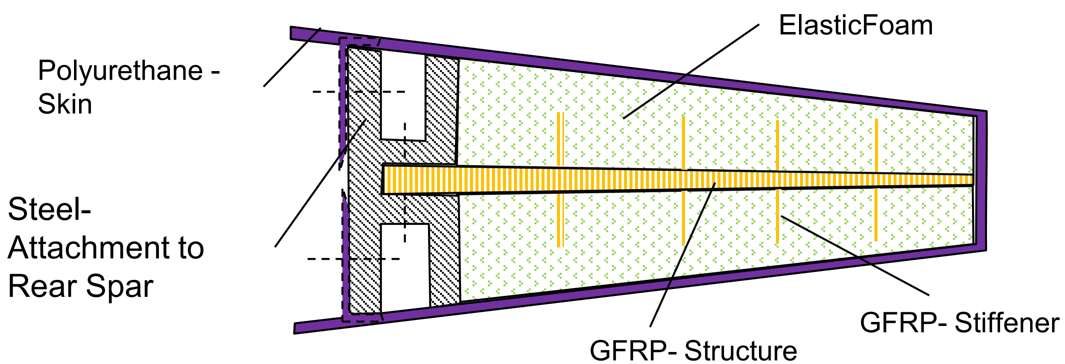
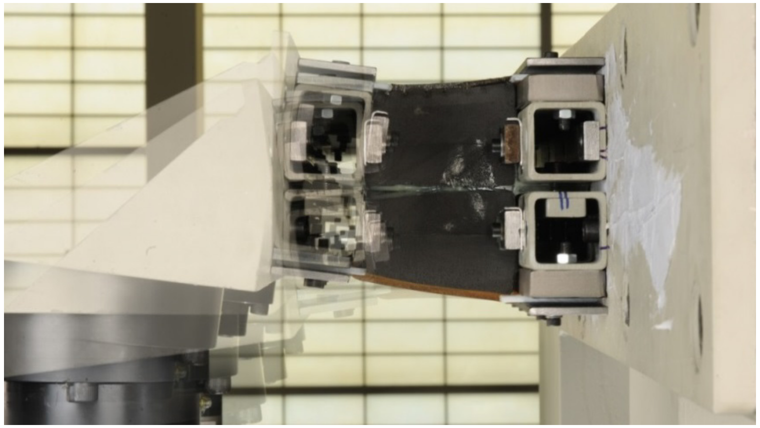


Fig.: Design Concept for Integrated Stiffeners and Material Combination

Approaches for skin design

Polyurethan with foam

- Development of a morphing trailing edge fin
  - Material combination of
    - GFRP
    - Polyethylene Foam
    - Polyurethane Skin
  - Coupon and Component Tests
    - Static material tests under environmental conditions i.e. temperature and marine water in combination
    - large scale cyclic component test



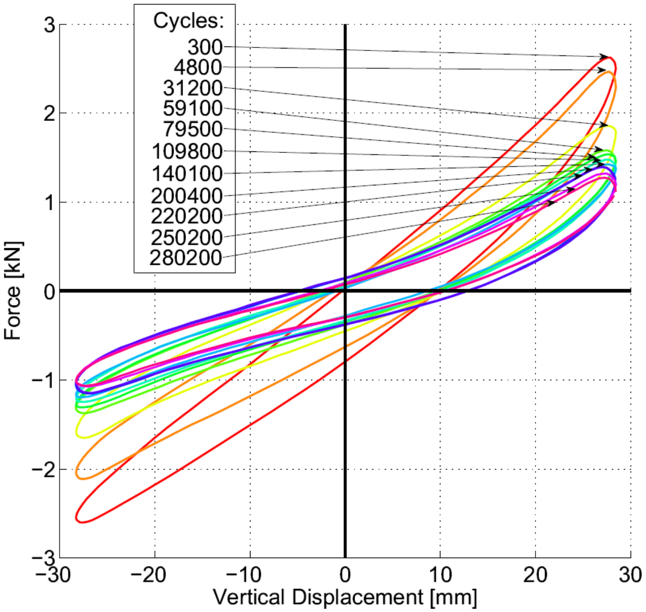
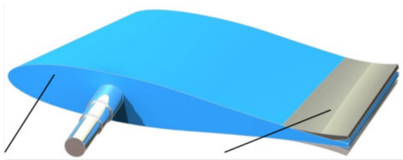


Fig.: Results of cyclic tests of the morphing trailing edge segment

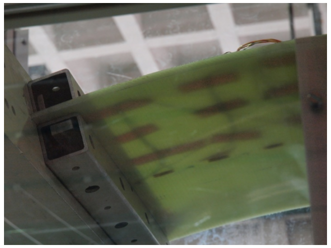
→SOURCE: Kintscher, M., Geier, S., Heinze, C., Pohl, M., Kamp van de, B.: Entwicklung einer flexiblen Hinterkante einer Stabilisatorflosse. DLR-Interner Bericht. DLR-IB 131-2014/22

Approaches for skin design
Polyurethan with foam

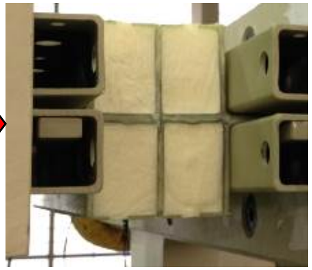
- Continuous increasing complexity and details in FEA Design combinesd with validation by experimental tests
  - Variant 0: 2-dimensional, GFRP
  - Variant 1: 2-dimensional, GFRP + PU-Foam
  - Variant 2: 2-dimensional, GFRP + different foams
  - Variant 3: 2-dimensional, GFRP + PE-Foam + PU-Skin
  - Variant 4: 3-dimensional, GFRP + PE-Foam + PU-Skin



Variant 0



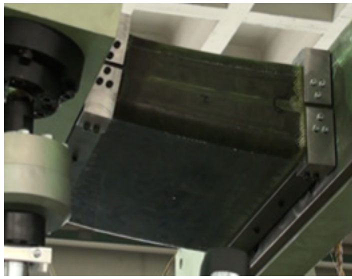
Variant 1



Variant 2

Variant 3

Variant 4



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Approaches for skin design
Polyurethan with foam

- Flexible Morphing Trailing Edge
- In-Service since 06/2014 on a marine vessel

Outlook – Main Challenges

- Concentration on conventional high-strain capable materials (GFRP, CRRP) for high acceptance in industrial applications →Structural Design/Good Ideas as enabler for industrial application

- Basic Research in terms of material combinations (GFRP/Elastomers, Compliant Mechanisms, Integration of Functionalities, Hydrophobic Surfaces)

- Manufacturing considerations (complex geometries, cost reduction, material wastage reduction) of these materials e.g. 3D printing of superelastic metals

- Concurrent optimization of skin and substructure kinematics as a whole, integrated system, including energy, weight and stress objectives and/or constraints